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RESEARCH MEMORANDUM

METHODS FOR CONNECTION TO REVOLVING THERMOCOUPLES

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SUMMARY

Several new methods have been devised for obtaining electrical connection to thermocouples that are revolving at high speeds. All the methods depend upon sliding metallic contacts. An essential feature of two of these methods is the use of an all-copper slip ring and brush system, which is operated under controlled scoring conditions in order to prevent the formation of chemical films on the surfaces of the sliding contacts.

Two general types of pickup system are described with modifications for special installations. One pickup system combines the copper brush and slip ring with an axially rotating center contact of the other thermocouple metal. The other pickup system employs slip rings and brushes of copper in both sides of the thermocouple circuit. In this system, a method of compensation is used to equalize the thermoelectric voltages that are generated in the junctions between the thermocouple materials and the copper circuits.

Both pickup systems have been proved to transmit an accurate signal from a revolving thermocouple to within ±0.045 millivolt at contact sliding speeds up to 5400 feet per minute. This speed corresponds to 22,000 rpm for 1-inch-diameter slip rings. The voltage variation corresponds to $\pm 1.9^{\circ}$ F on the chromel-alumel temperature scale and to $\pm 1.5^{\circ}$ F on the iron-constantan scale. These errors are maximum; the average is indeterminate and much smaller.

INTRODUCTION

Research on aircraft engines at the NACA Lewis laboratory has required the development of methods for transmitting signals from revolving thermocouples to the stationary measuring circuits. Among the many applications of revolving thermocouples are those for measuring the temperatures of turbine and compressor blades in gas-turbine engines and the temperature of anti-icing equipment on aircraft propellers.

A major problem in the use of revolving thermocouples is to obtain connection between the stationary and revolving circuits in such a manner as not to superimpose electrical disturbances on the true signal. The problem resolves into a research on methods for either eliminating or minimizing all undesirable electromotive forces caused by sliding contacts, thermal junctions, and induction. The problem also includes the elimination of transient effects found to exist under certain conditions in ball bearings.

Research has shown that one method for conducting a practically true signal in null circuits through a sliding contact system is to employ pure copper brushes and slip rings operated deliberately under controlled scoring conditions so as to eliminate slip-ring film formations, which ordinarily produce loss of sensitivity by increasing resistance at the sliding surfaces.

The technique of operating a copper brush and slip ring under scoring conditions was applied to two general types of pickup system. One pickup system combines the copper brush and slip ring with an axially rotating center contact of some other metal. This system is known as the center-contact method. Where copper forms one entire side of the thermocouple circuit, the upper temperature limit is determined by the copper. This temperature limit can be avoided by the use of other thermocouple metals and copper slip rings in conjunction with compensation. Another pickup system employs slip rings and brushes of copper in both sides of the thermocouple circuit; all junctions between the thermocouple materials and the copper circuits are contained in an equilibrium temperature zone. This system is known as the compensated-thermocouple pickup method and is more widely used than the center-contact method. These two pickup methods are described herein with the methods and the tests used in determining the accuracy in transmitting thermocouple signals.

COMPENSATED-THERMOCOUPLE PICKUP METHODS

Principle of operation. - The basic components of the compensated-thermocouple pickup method are illustrated by the schematic diagram of figure 1. The revolving measuring thermocouple T_1, comprising two metals, connects to copper leads at C_1 and C_2. These connections are in intimate thermal contact and are located in a zone of equilibrium temperature. The copper circuits continue from C_1 and C_2 through the copper slip rings and copper brushes to connections C_3 and C_4 where these circuits revert to the thermocouple metals. Connections C_3

and C_4 are located in the same temperature zone as connections C_1 and C_2. The thermocouple metals continue to the measuring potentiometer, which may have automatic compensation for the reference junction T_4 of the thermoelectric system.

When temperature T_2 is equal to T_3, the electromotive forces that are generated at connections C_1 and C_2 are equal but opposite in polarity to those generated at connections C_3 and C_4. Consequently, the relation of voltage to temperature between thermocouples T_1 and T_4 is not disturbed electrically regardless of the composition of the thermocouple metals.

An arrangement of the parts in a practical shaft-end compensated pickup unit is illustrated in figure 2. The unit is designed for four thermocouples but only one complete circuit is shown. The design may be equipped with its own mounting base and bearings, resulting in a unit such as is shown in figure 3.

Brush design. - Investigations of various brush designs resulted in the adoption of the cantilever brush with center loading. This type of brush (fig. 2) was found suitable for use at high rotating speeds under conditions of unavoidable vibration and slip-ring eccentricity.

A practical brush design was found to consist of a 1/8-inch round contact shoe set into one end of a phosphor bronze cantilever spring 7/32-inch wide by 0.024-inch thick and about 2 inches long between the brush shoe and the first point of contact with the brush mounting base. A copper pigtail was attached directly to a small protrusion on the brush shoe so that the bronze of the brush spring was not included as part of the thermoelectric circuit.

Brush loading was obtained with an adjustable loading screw located so as to bear on the exact center of the brush spring. The required total brush load was found to be between 7 and 8 ounces for brushes of 1/8- to 5/32-inch diameter. Less loading resulted in open brush circuits at high speeds, whereas greater loading caused unnecessary brush wear and excessive brush heating.

In the laboratory investigation, all the copper slip rings and brushes were fabricated from the same piece of master stock in order to minimize electromotive forces found to be present in sliding contacts of slightly dissimilar copper. The brush circuits were closed with a magnetic solenoid brush actuator, as shown in figure 2. It was found that the brush circuits should not be closed for periods exceeding 30 seconds at any one time. Longer closed-circuit periods produced oxidation films on the slip rings with most lubricants. One method that was found to eliminate completely the formation of these films was to operate the brushes under controlled scoring conditions in the presence of lubricants having low gumming tendencies. Even this procedure does not prevent oxidation where the brush temperature is allowed to exceed a mass temperature limit of about 300° F. By using short contact periods under scoring conditions, the brushes maintain freshened surfaces having low electrical contact resistance. Brush wear under these conditions is severe but is within tolerable limits of several hundred hours service when specific lubricants are used. One of the satisfactory service lubricants consists of light instrument oil containing about 1 gram per liter of colloidial graphite.

Laboratory investigation. - The laboratory apparatus used to evaluate the errors introduced by the compensated-thermocouple pickup system is shown in figure 4. All shafts were electrically grounded through grounding brushes in order to eliminate voltage transients that were found to be generated in the ball bearings when operating at high speeds. The revolving thermocouple is designated T_1, and the stationary calibration reference thermocouple T_c. The slip-ring diameter was 1.0 inch.

The equilibrium temperature zone shown in figure 4 was modeled after the hypsometer chamber described in reference 1. This type of chamber is effective in preventing temperature transients in the zone. This zone-chamber design is more elaborate than is generally necessary for routine service. A simplified model is subsequently described. In the accuracy-evaluation investigation, steam was the accepted medium for use in the equilibrium temperature zone chamber. Steam and moisture-saturated compressed air were used as calibration media.

The results of a few of the accuracy tests are presented in figure 5 as temperature differences between the revolving thermocouple and the reference thermocouple for a range of slip-ring surface speeds up to approximately 5400 feet per minute. The data for air and steam are in good agreement and indicate an average error of only 0.75° F and a maximum error of 1.3° F on the chromel-alumel temperature scale.

The initial observation shown at zero speed in figure 5 is the small initial difference between T_1 and T_c thermocouples. This difference was again observed after the speed tests were completed.

The equilibrium temperature zone chambers shown in figures 2 and 3 are simplified models of the steam hypsometer chamber of figure 4. The function of the zone chamber is fulfilled only when the temperatures of the T_2 and T_3 junctions are exactly equal. A large immersion depth of these junctions and their protection tubes is necessary as insurance that both sets of junctions attain the temperature of the zone chamber. Conversely, in order to avoid vibrational breakage at high rotational speeds, the immersion depth of the revolving tube was limited to 10 diameters, which is less than the required immersion depth discussed in references 3 to 4, especially for steam atmospheres.

Special design requirements were imposed on the construction of the rotating protection tubes and zone chamber to offset the low immersion depth required for durability at high speeds. The inside diameter of both protection tubes depends upon the number of thermocouple junctions they must contain. The immersion factor of these tubes was minimized by using the smallest-diameter and thinnest-walled tubing possible in conjunction with the least number of thermocouples of the smallest practical wire gage. The tubes and the chamber were made of thin polished stainless steel. The base of the revolving tube was fitted with a disk, which acted as a combination slinger ring and heat-transfer fin. The fin was located close to the gasket end of the zone chamber. The gasket was made of neoprene and was purposely fitted loosely so that steam escaped over the fin continuously. The steam inlet was directed toward the gasket end of the chamber because the heat losses at this end are usually greater than the losses at the domed end.

Reflective surfaces on the zone chambers are used for the same reasons they are used in precision hypsometers; namely, to protect the interior of the chamber from changes of temperature that might be caused by radiation to or from the walls of the chamber. Where the installation involves nearby ducts having high wall temperatures, the zone chamber is enclosed in a second reflective shield or shroud. In the presence of high external temperatures or radiation, the zone chamber shown in figure 4 may be used. Heat loss through the zone-chamber mounting clamps is minimized by reducing thermal contact between the zone chamber and its clamp, as can be seen in figure 3.

The steam supplied to the zone chamber is usually saturated, and provision is made for preventing accumulations of the condensate in the steam cavity. The outlet line from the zone chamber was vented to barometric pressure just below the chamber, as shown in figure 2. Thus, in addition to equilibrium, a known temperature was established at the barometric steam point. This point serves as a reference temperature for testing the circuits under service conditions.

Moisture-saturated air was found to be a suitable substitute for steam in cases where external radiation sources were not present in the vicinity of the zone chamber, although this practice is not recommended where bearings are installed between the slip-ring assembly and the T_2 tube. All thermocouple pickup bearings are air-oil mist lubricated in order to avoid bearing overheating.

Switching circuits. - The number of thermocouples that can conveniently be used with the compensated thermocouple pickup method (fig. 2) is limited for mechanical reasons. This circuit is best adapted to a maximum of approximately six thermocouples because one pair of slip rings and T_2 junctions are required for each measuring junction. With more than six measuring junctions, the required diameter of the protection tube for the T_2 junctions becomes too large to permit the use of the proper immersion depth at high speeds.

Where numerous thermocouples are required, a remotely controlled selector switch may be built into the revolving shaft of the pickup unit. A schematic example of a revolving thermocouple pickup switch is shown in cross section in figure 6. The general mechanical arrangement consists of a switch plunger actuated by means of a sliding collar that slides on and revolves with the shaft. The collar is positioned by means of a "Y" yoke, which is in turn positioned by means of suitable automatic-control motors.

The switch of figure 6, with slight modification, may be used with either of two similar circuits and with from 24 to 60 measuring junctions. In one circuit, all T_1 leads continue through the switch and into the zone chamber where they join the copper circuits. In this case all switch contacts and switch arms are constructed of thermocouple metal so as to avoid undesirable thermal effects. A pickup unit of this type is shown in the photograph of figure 7, where the steam-zone chamber is located at the end of the shaft.

The other circuit for use with the revolving switches requires that the zone chamber be located between the pickup unit and the machine under test. In this case, the link shaft between the pickup and the machine contains the T_2 junctions, and passes through the zone chamber. The zone chamber is usually equipped with a steam inlet at each end and with a center steam outlet. A side-entrance thermocouple well is provided for containing the T_3 junctions. In this switch all switch parts are made of copper. A pickup unit of this type is shown in figure 8. In both switches of figures 7 and 8, the thermocouples are divided into two groups of 12 each, thus permitting the use of a square switch compartment. In pickup units for 60 thermocouples, the switch is octagonal in form with 15 thermocouples in each of the four groups.

Equilibrium temperature zones using liquids. - Space limitations sometimes require special designs of pickups in which the pickup itself becomes an inherent part of the machine under test. In certain cases it has been found convenient to use either the cooling liquid or the fuel that is used in the machine to equalize the temperature in the zone chamber.

A liquid-zone system, which represents the case of a jet-driven rotor using fuel as the zone control media, is schematically illustrated in figure 9. Fluid flow is over the T_3 junctions and thence over the T_2 junctions. Both groups are located close together inside the fluid compartment.

The use of liquids in the equilibrium temperature zone does not always produce the desired temperature equilibrium. Uneven temperature distribution, caused by stratification of heated fluid layers, and cavitation may exist at high rotational speeds. In one case a stratified heated water film from a bearing elevated the T_2 junction temperature 10° F above that of the T_3 junctions. In another case the fluid cavitated so as to expose completely the T_2 junctions with a resultant error of -20° F. In most cases, both stratification and cavitation have been overcome by merely installing restrictions in the outlets of the zone compartment. Such restrictions are illustrated in figure 9.

Applications where shaft ends are inaccessible. - Where shaft ends are inaccessible, the compensated method may be applied by the simple expedient of designing the zone chamber as a divided shroud, which is used to enclose the revolving T_2 junctions in a suitable steam zone. This method is illustrated in figure 10. The revolving T_2 junctions are either installed in the rim of a revolving annular ring having low thermal conductivity from the rim to the shaft or these junctions may be disposed radially in small protection tubes made from hypodermic needles.

Resistance-compensated thermocouple pickups. - The stationary T_3 thermocouples ordinarily used for sensing the temperature of the zone chamber may be replaced by a properly adjusted resistance element such as is used as the compensating element in compensated potentiometers. With this circuit copper leads are used between the pickup unit and the instrument. This all-copper extension circuit is especially adapted to the elimination of errors due to stray induction in long-lead systems where the instrument must be located at a point some distance from the pickup unit. Another use for the circuit is in the conservation of metal where rare-metal thermocouples are used for extreme temperatures. In these cases, the rare metal is installed only between the T_1 measuring junctions and the T_2 reference junctions. The circuit is schematically shown in figure 11.

CENTER-CONTACT THERMOCOUPLE PICKUP METHODS

Principle of operation. - In the simplest rotating thermocouple pickup system, the thermocouple signal is transmitted through contacts located on the axis of rotation at each end of the rotating shaft. Each contact is made of the thermocouple metal that comprises that part of the circuit. Point-contact at the center of rotation permits the use of metals other than copper without disturbing the measured signal. When only one end of the rotating shaft is available, the center contact is employed as one side of the circuit and a copper brush and copper slip ring as the other side. Although the pivot contact can be made of any thermocouple metal, the brush and slip ring circuit is limited to those metals that do not generate disturbing electromotive forces due to sliding.

When copper is used for the entire brush, the slip ring, and one side of the circuit, the measuring thermocouple is limited to the temperature range of copper against other thermocouple metals. When copper is used for the brush and slip-ring circuit, then a compensation method permits the use of metals other than copper at the measuring junction. The temperature range of the center-contact method may be extended beyond that of copper without compensation by employing an iron slip ring and iron brush,which is lubricated with sulphurized extreme-pressure lubricant. This method is a special case and is not in service use as yet.

Laboratory investigation. - The apparatus used to evaluate the accuracy with which signals were transmitted through the center-contact copper-constantan pickup system is illustrated in figure 12. Steam was used as the calibrating medium. The test procedure consisted in observing the temperature differences between T_1 and the calibration thermocouple T_c for various revolving speeds of T_1. As with the previously described apparatus used to test the compensated-thermocouple pickup method, all the shafts were grounded and a bifilar-spiral winding was used on the lead wires where they passed through the motor shaft in order to minimize the pickup of stray induction.

The data plotted in the curve of figure 13 represent the largest temperature differences observed at each speed in no less than five and, more often, ten observations. The largest single difference was -0.6° F.

Pickup design considerations. - A schematic drawing of a center-contact unit that has been used in bearing-lubrication investigations up to speeds of 50,000 rpm is shown in figure 14. The unit was designed with minimum diameters of all rotating parts in order to obtain low surface speed at the copper slip ring. The effective mean radius of the brush track on the slip ring was 1/8 inch. Because of the small radius, the slip ring surface speed was about 3200 feet per minute at 50,000 rpm. At 3200 feet per minute, a pure copper brush and slip ring generates not more than 0.01 millivolt. In terms of temperature, this electromotive force amounts to 0.37° F on the copper-constantan temperature scale in the region of 200° F.

A "Y" shaped frame of bronze was used to support double copper brushes, as shown in figure 14. The constantan center contact was mounted within the arms of the bronze frame so that all three circuits could be simultaneously closed by one push button. The arrangement shown in figure 14 was found to be free from the effects of vibration and to have the same sensitivity regardless of speed.

The center-contact pickup system previously described can be used only in systems with one measuring thermocouple. The revolving switch design shown in figure 8 is adaptable to this center-contact system for use with numerous thermocouples. Where the measuring junctions have a common ground on the machine, however, then the switch must be arranged with only one linear bank of contacts in order to avoid short circuits between the junctions.

CONCLUDING REMARKS

The investigation described herein has resulted in the development of methods for reading thermocouple temperatures on rotating machinery that introduces errors less than ± 0.045 millivolt (or $\pm 1.9^{\circ}$ on the chromel-alumel scale and $\pm 1.5^{\circ}$ F on the iron-constantan scale). Rotating switches (22,000 rpm for 1-in.-diam. slip ring) have been developed that permit reading of several thermocouples through a single pair of slip rings.

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REFERENCES

1. Mueller, E. F., and Sligh, T. S., Jr.: Laboratory Hypsometer. Jour. Optical Soc. Am., vol. 6, no. 9, Nov. 1922, pp. 958-964.

2. Roeser, Wm. F., and Wensel, H. T.: Methods of Testing Thermocouples and Thermocouple Materials. RP 768, Nat. Bur. Standards Jour. Res., vol. 14, no. 3, March 1935, pp. 247-282.

3. Fishenden, M., and Saunders, O. A.: The Errors in Gas Temperature Measurement and Their Calculation. Jour. Inst. Fuel, vol. XII, no. 64, March 1939, pp. S5-15; discussion, pp. S82-107.

4. Roeser, W. F.: Thermoelectric Thermometry. Temperature - Its Measurement and Control in Science and Industry, Reinhold Pub. Corp., 1941, pp. 180-205.

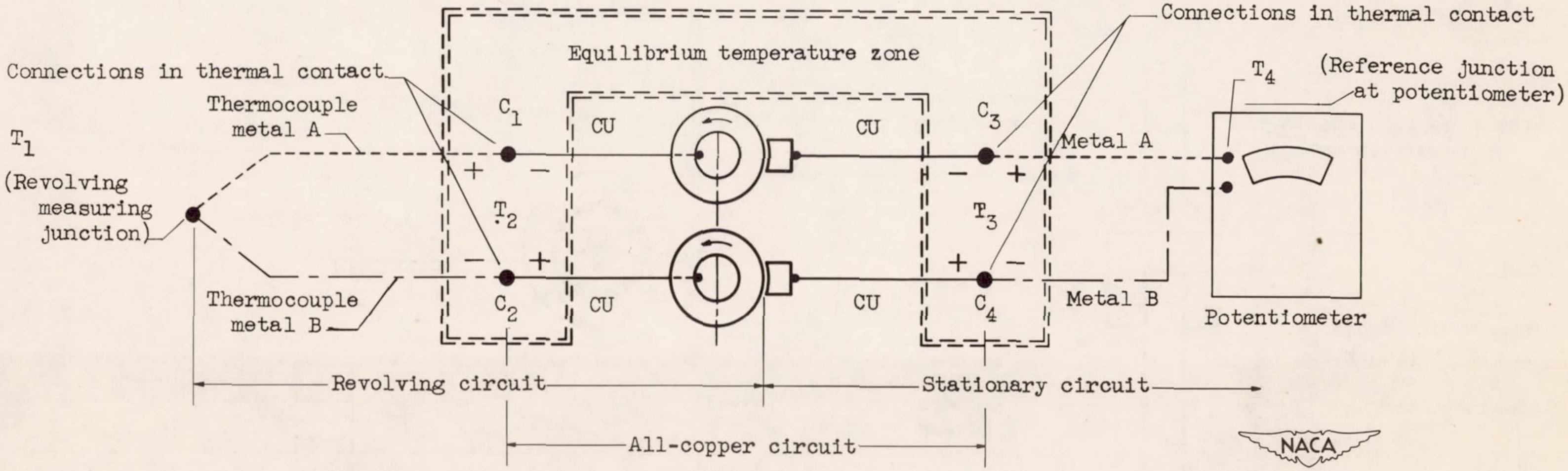


Figure 1. - Schematic diagram of compensated thermocouple pickup system.

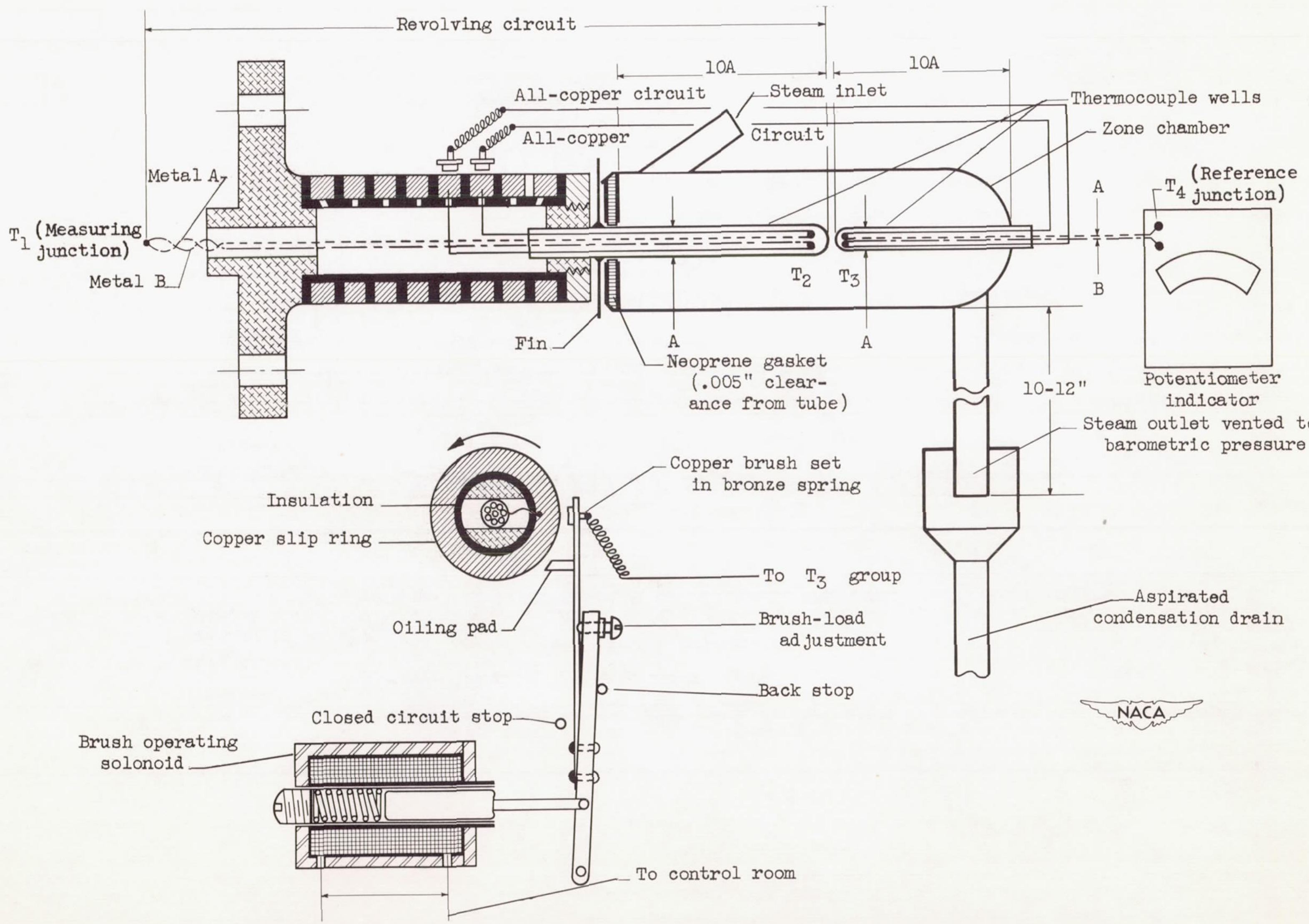


Figure 2. - Arrangement of parts in practical shaft-end pickup of compensated type.

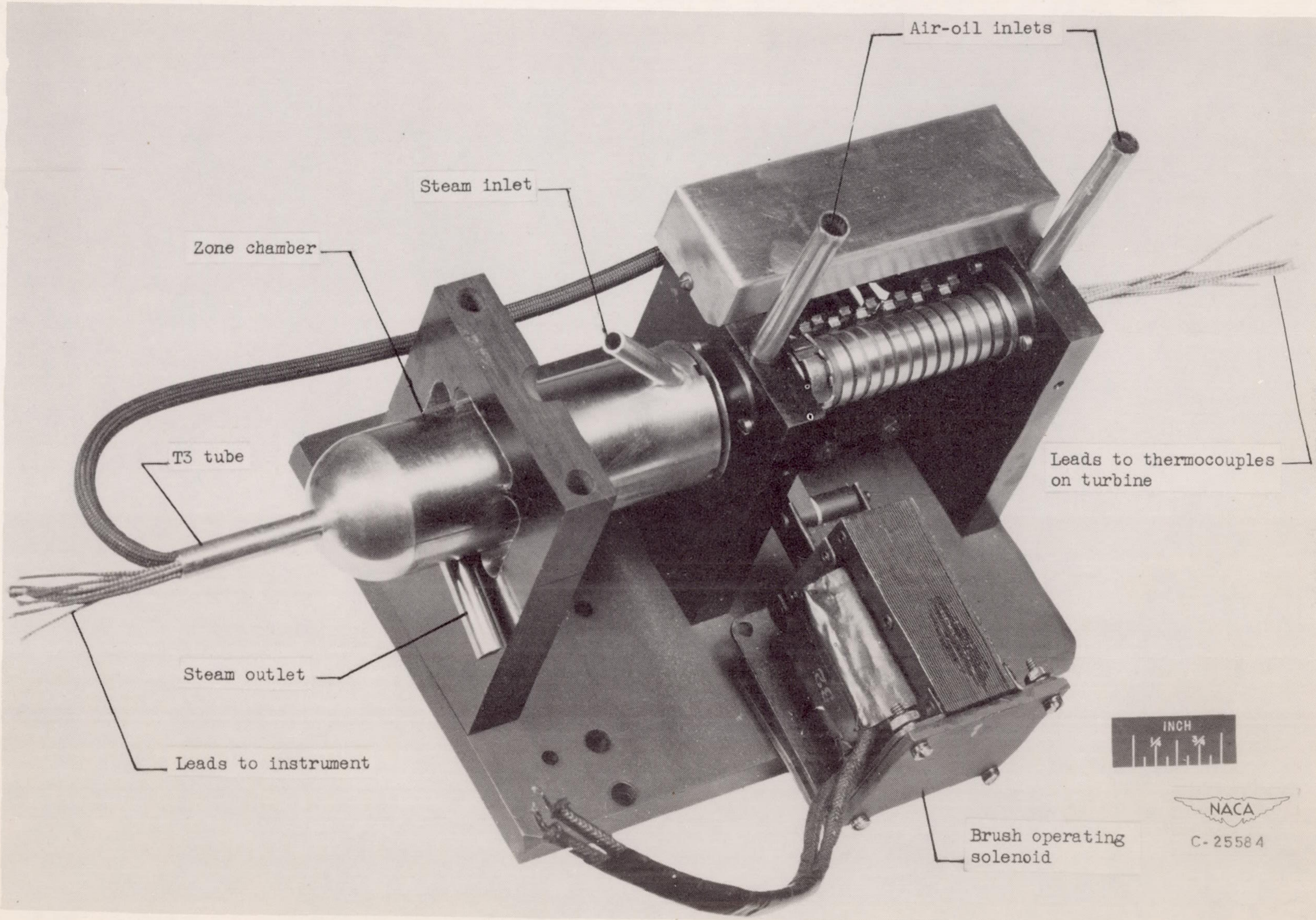


Figure 3. - Compensated 6-junction thermocouple pickup using circuit shown in figure 2.

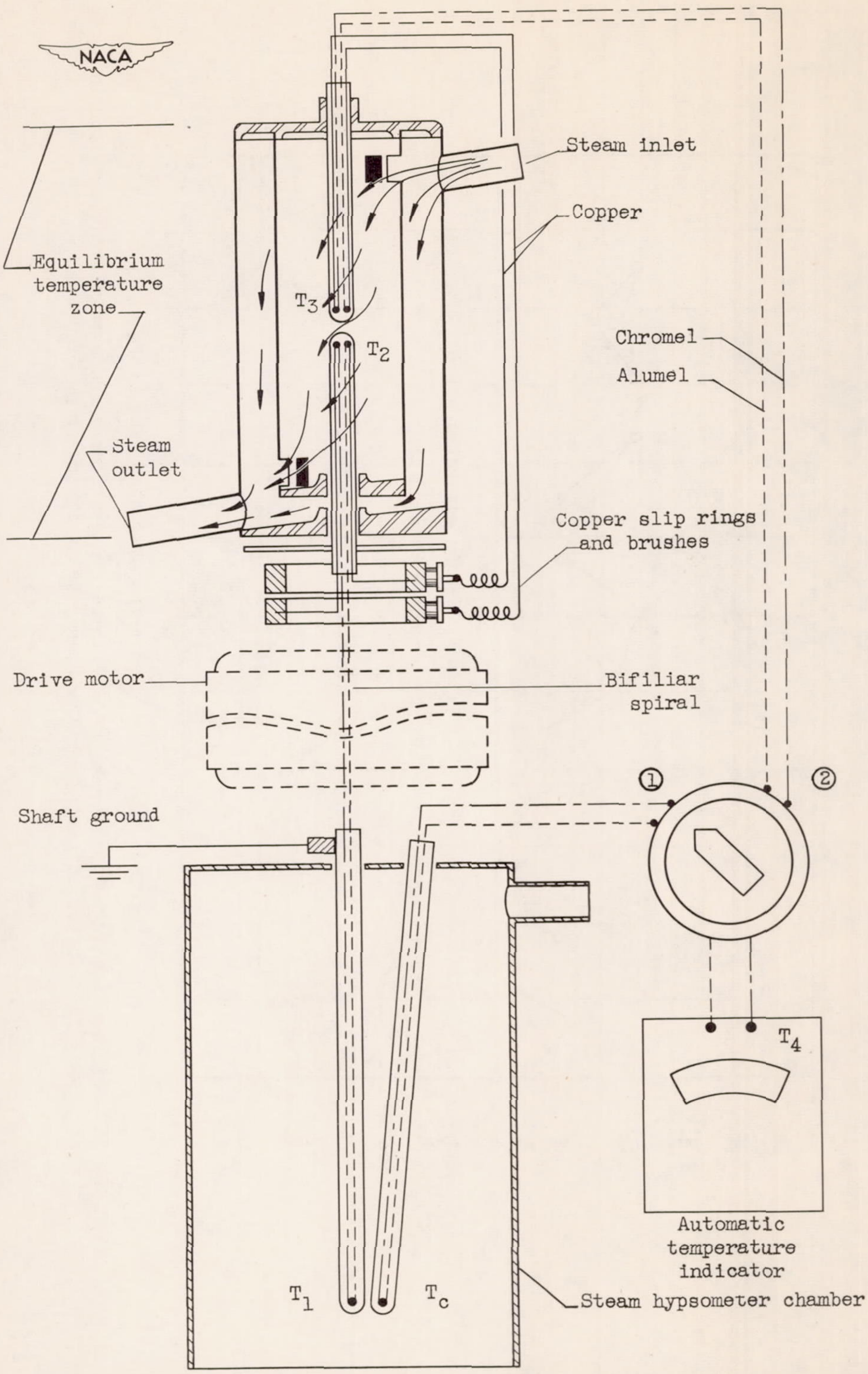


Figure 4. - Laboratory apparatus for measuring signal error through compensated thermocouple pickup system.

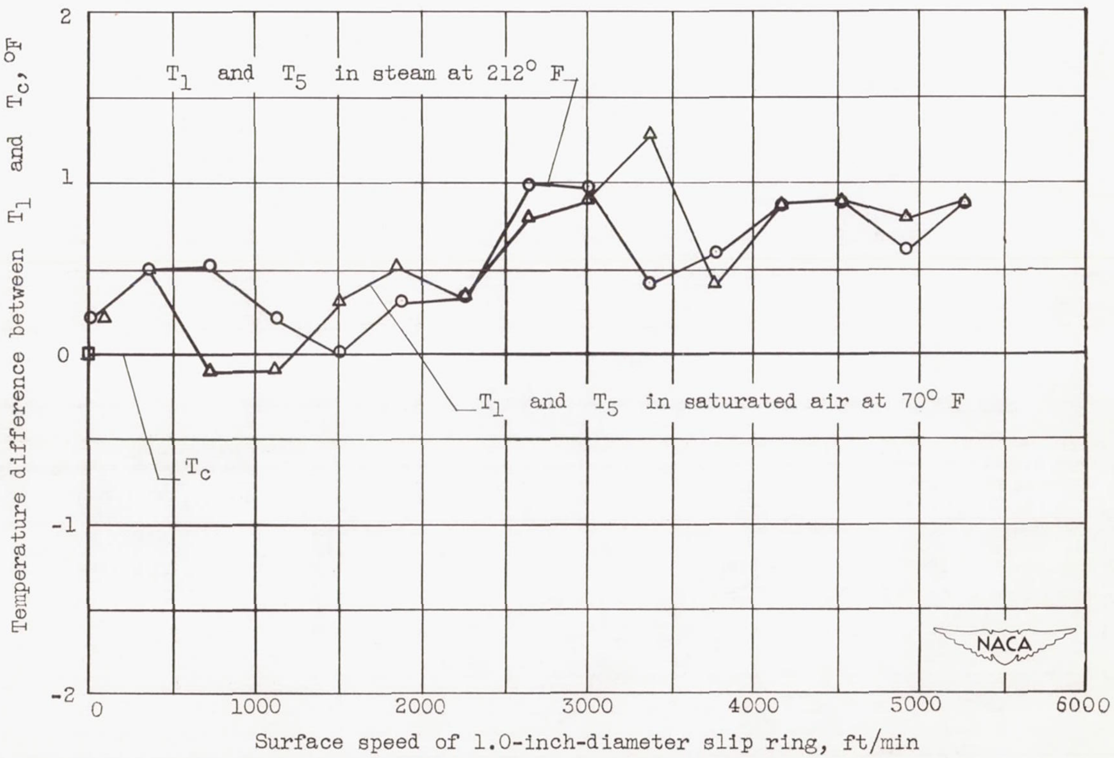


Figure 5. - Differences in indicated temperature between a stationary and a revolving thermocouple as a function of slip-ring surface speed, using apparatus of figure 4.

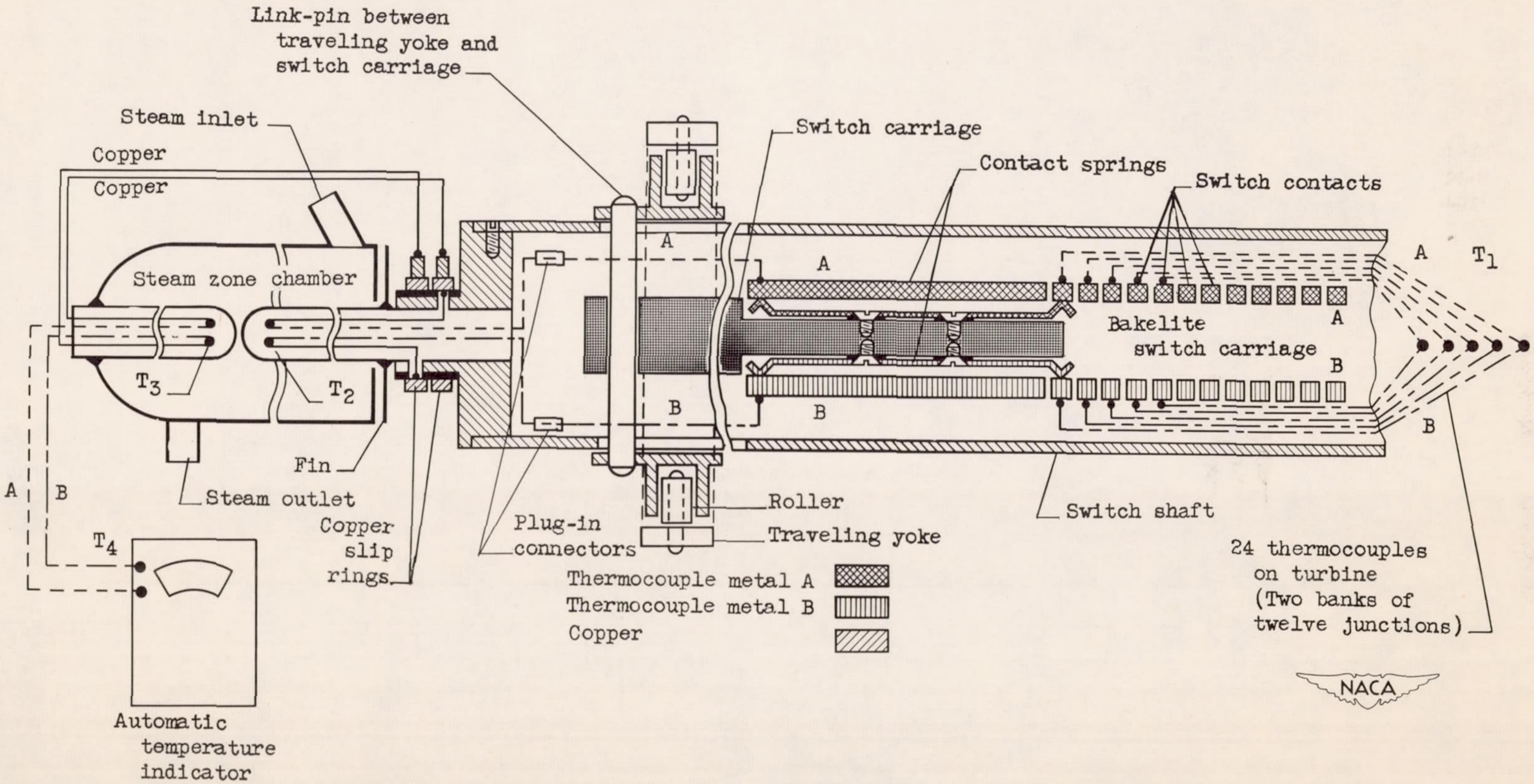


Figure 6. - Schematic diagram of compensated thermocouple pickup switch.

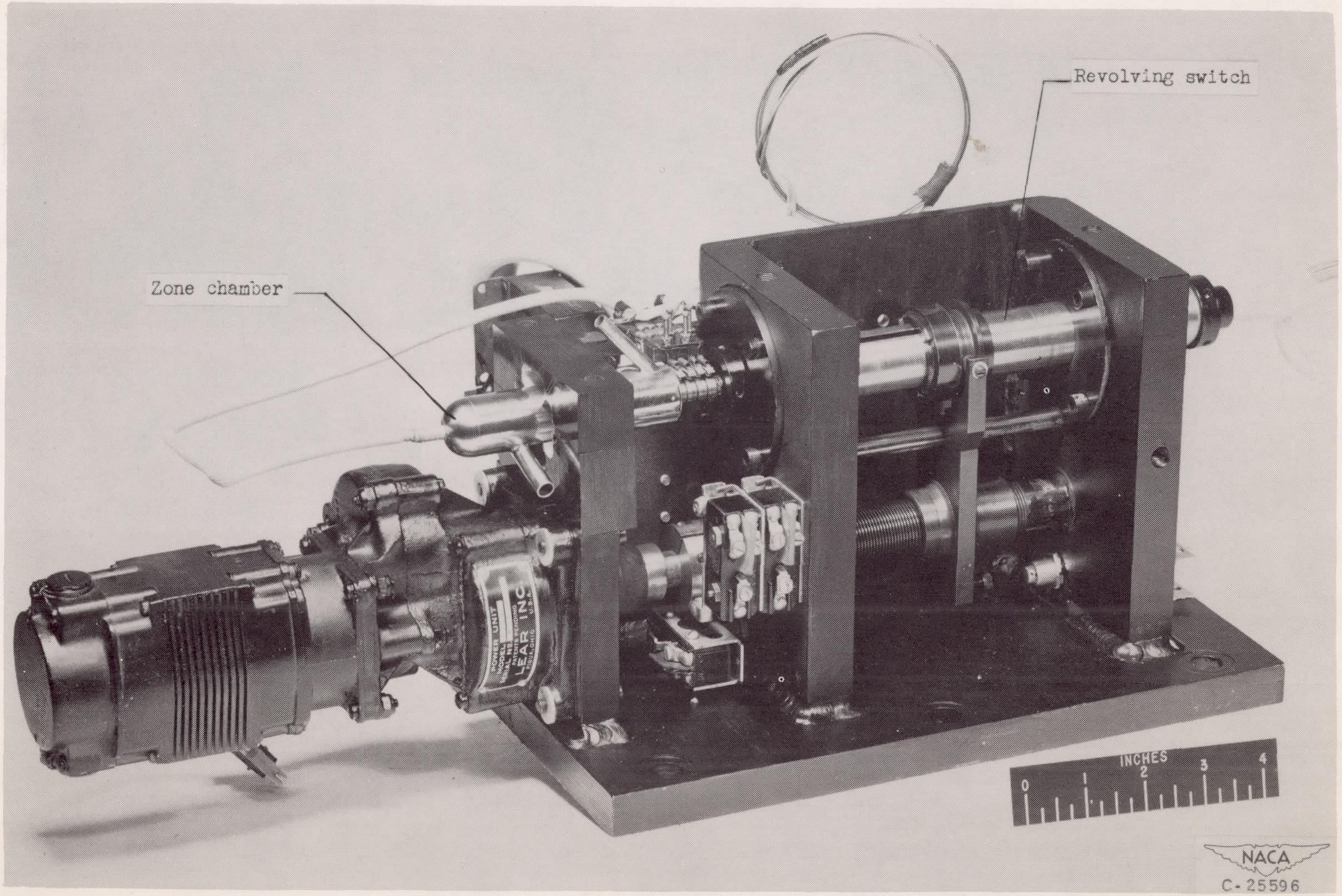


Figure 7. - Compensated thermocouple pickup and automatic switch with end zone chamber.

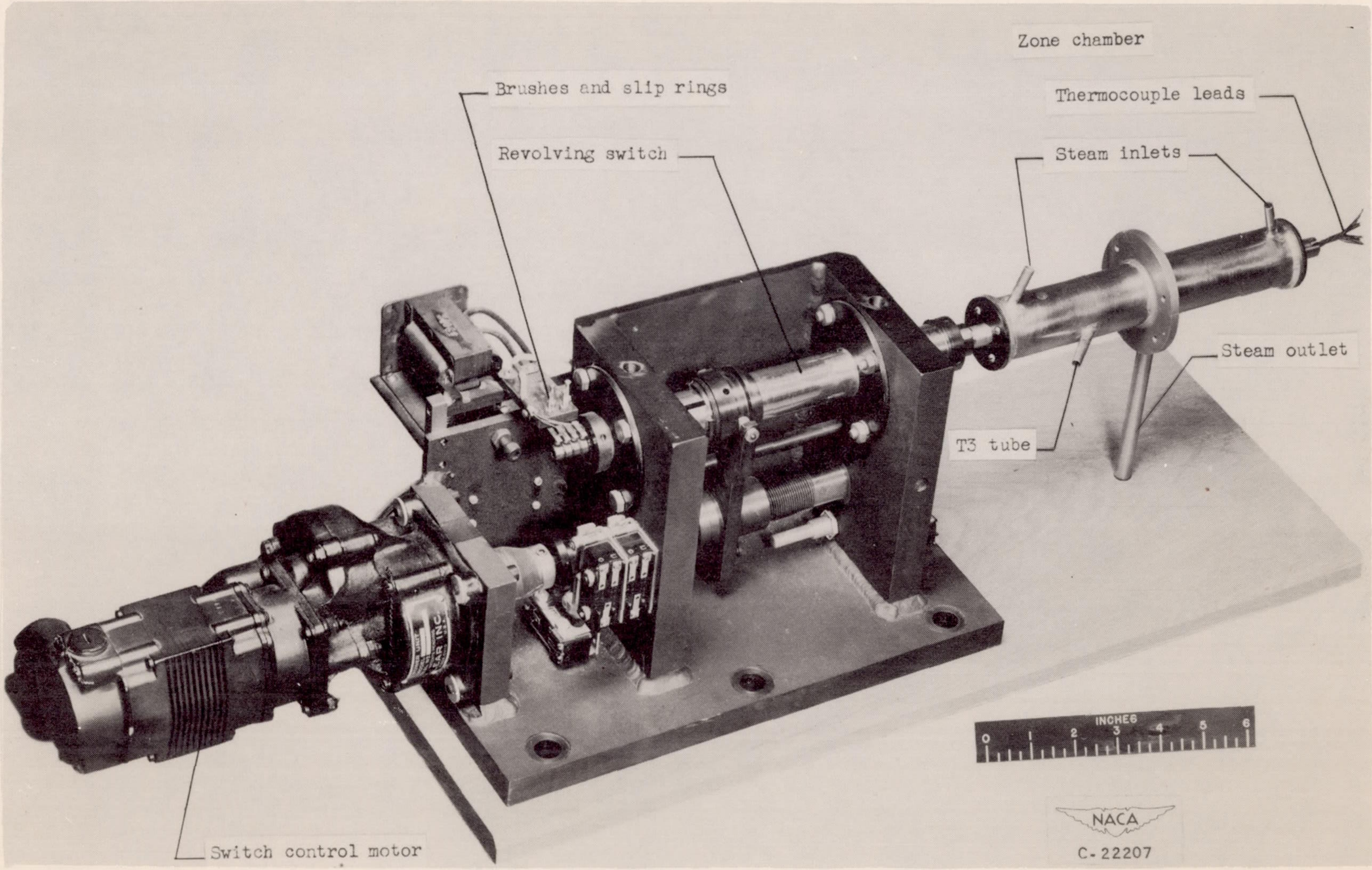


Figure 8. - Compensated 24-junction thermocouple pickup using center-type zone chamber.

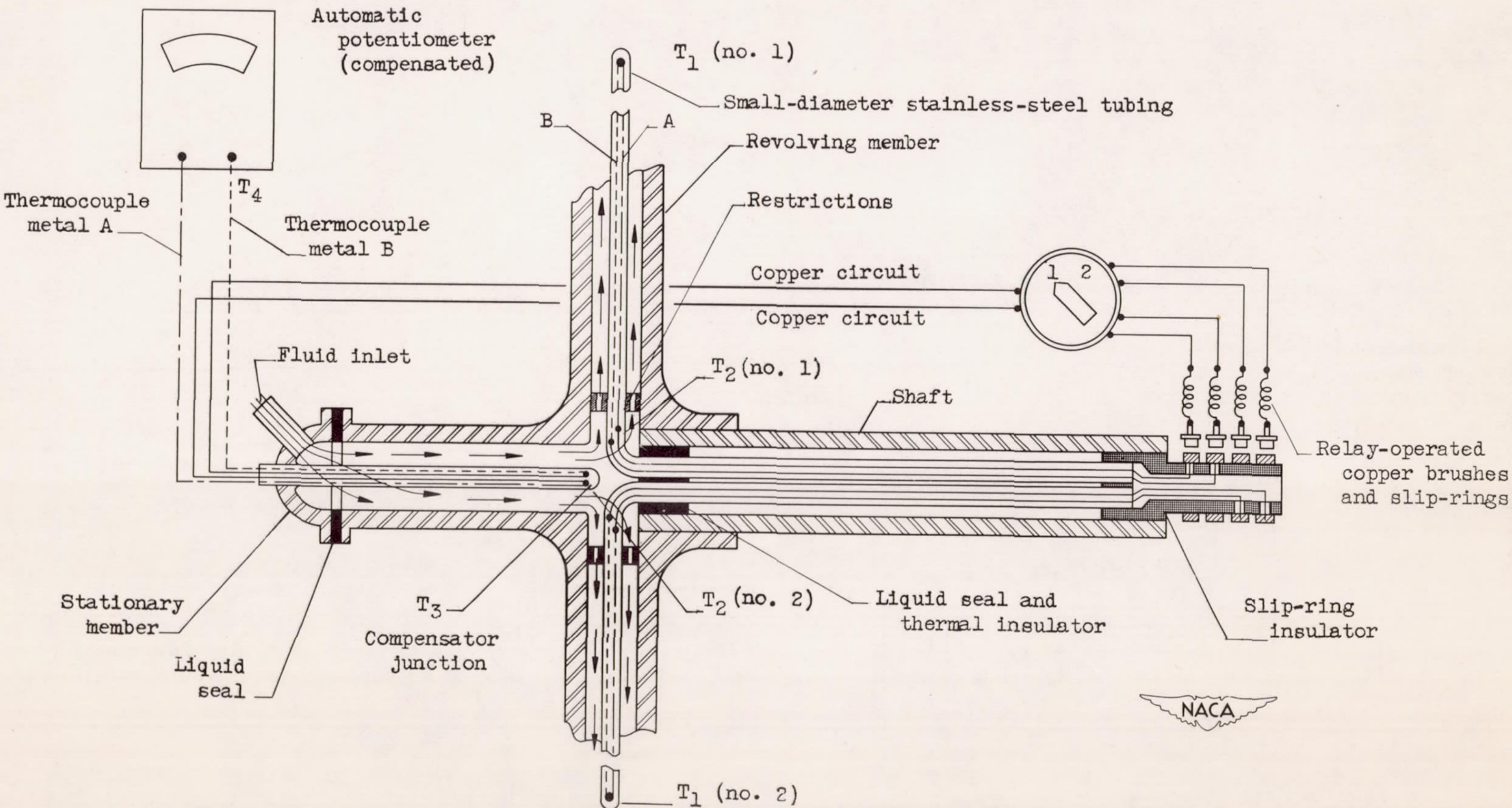


Figure 9. - Compensated thermocouple pickup system using liquid as zone-control media.

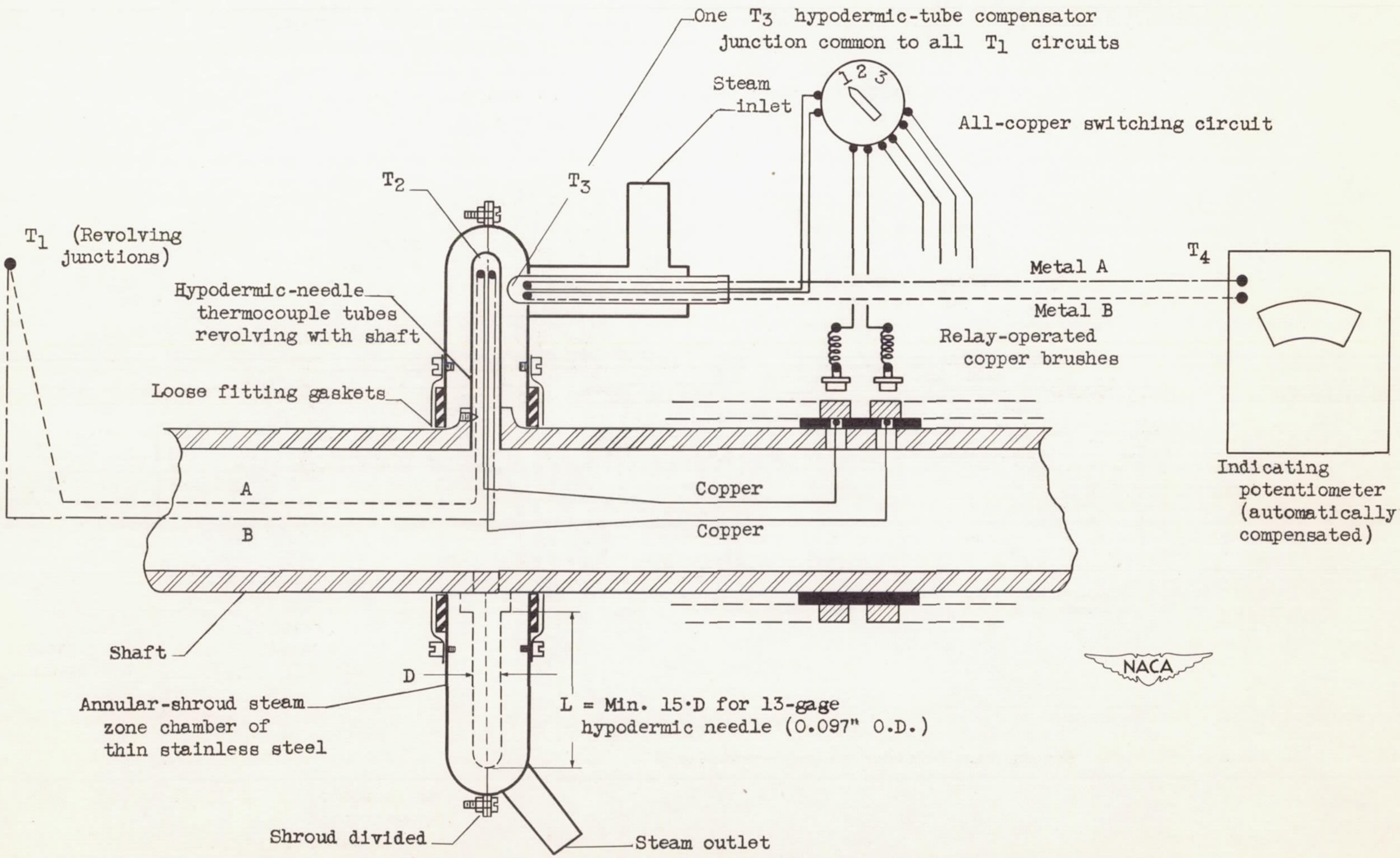


Figure 10. - Application of compensated pickup method where shaft ends are inaccessible.

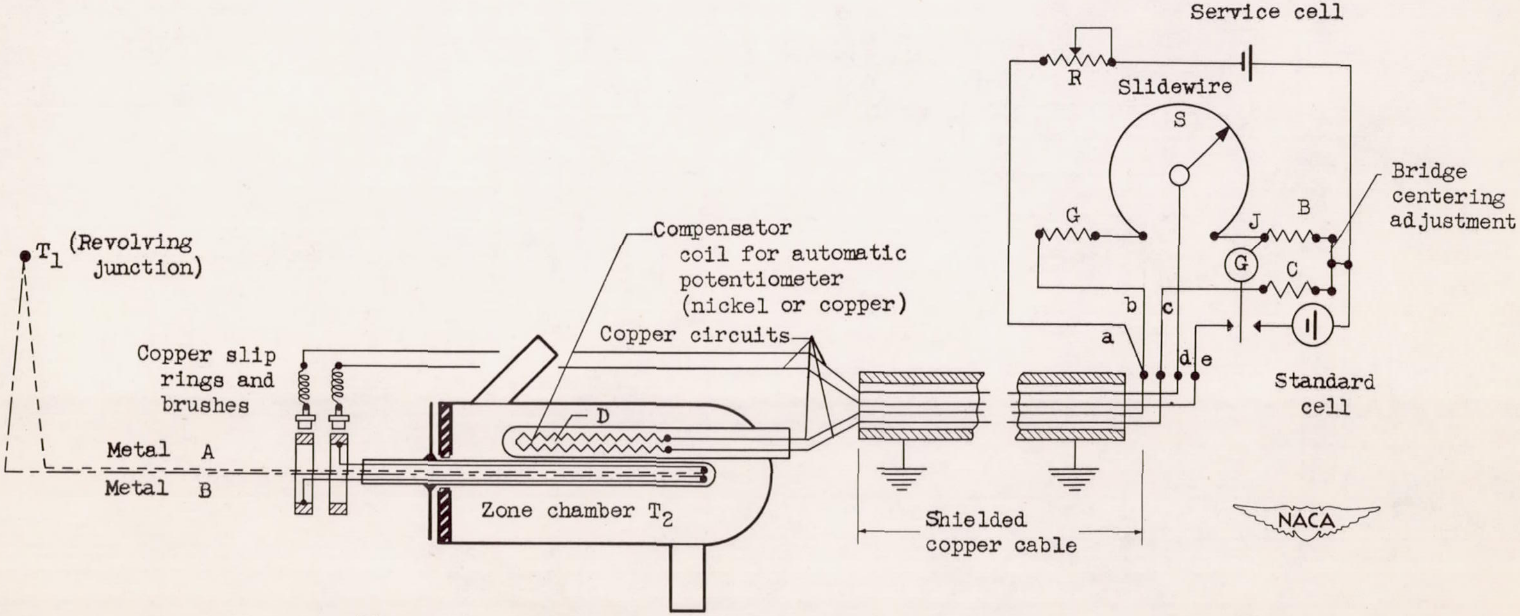


Figure 11. - Resistance compensated thermocouple pickup.

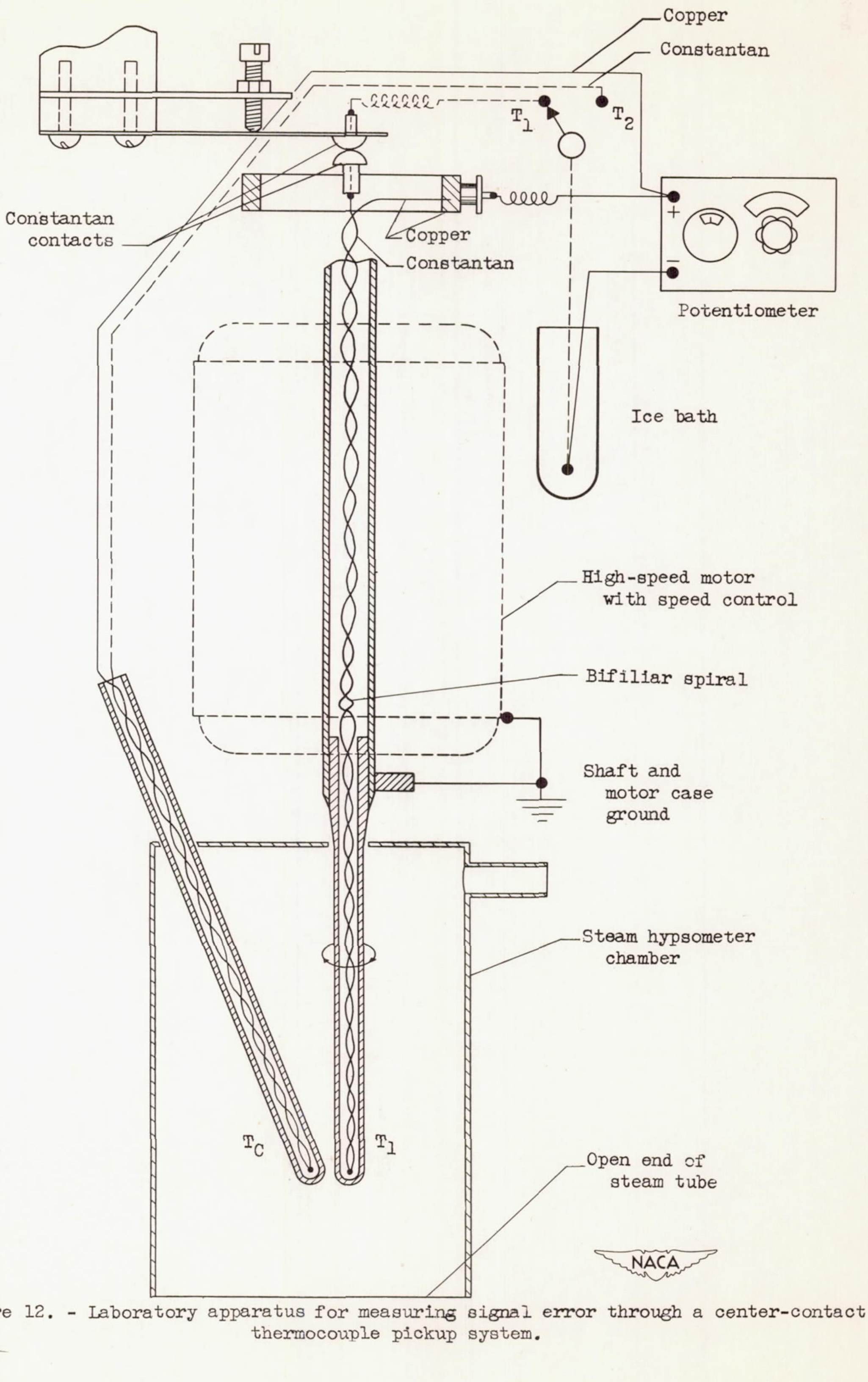
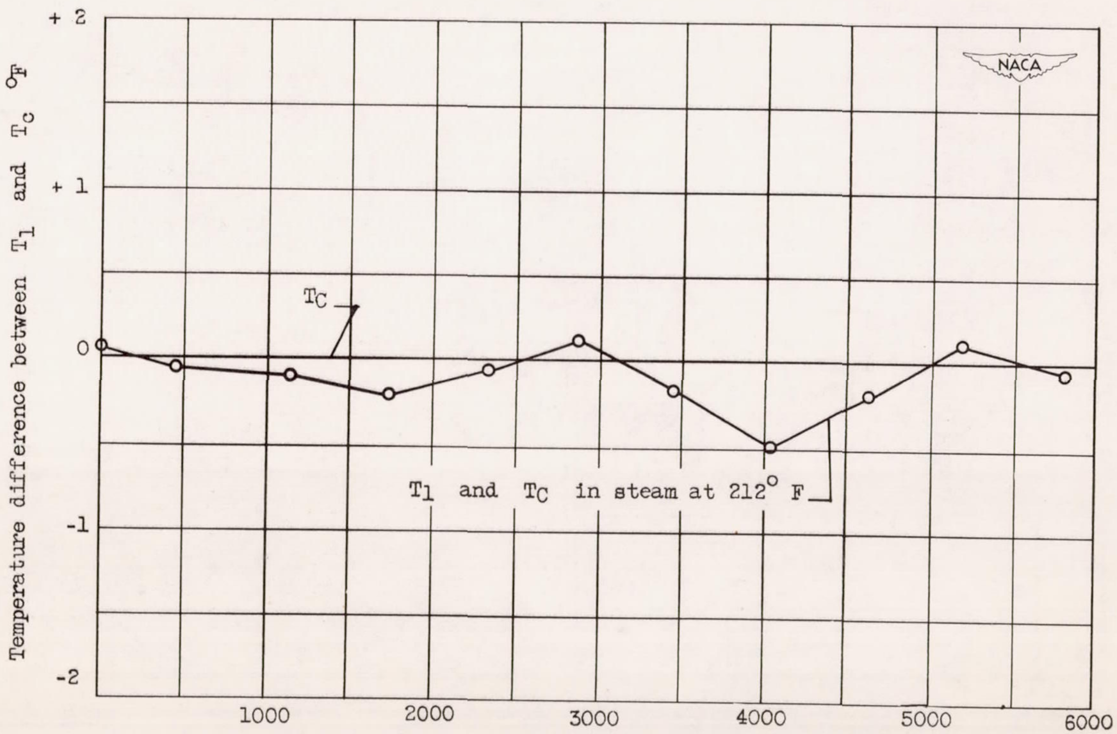


Figure 12. - Laboratory apparatus for measuring signal error through a center-contact thermocouple pickup system.



Surface speed of 1.5-inch-diameter slip ring, ft/min

Figure 13. - Differences in indicated temperature between a stationary and a revolving thermocouple as a function of slip ring surface speed using apparatus of figure 12.

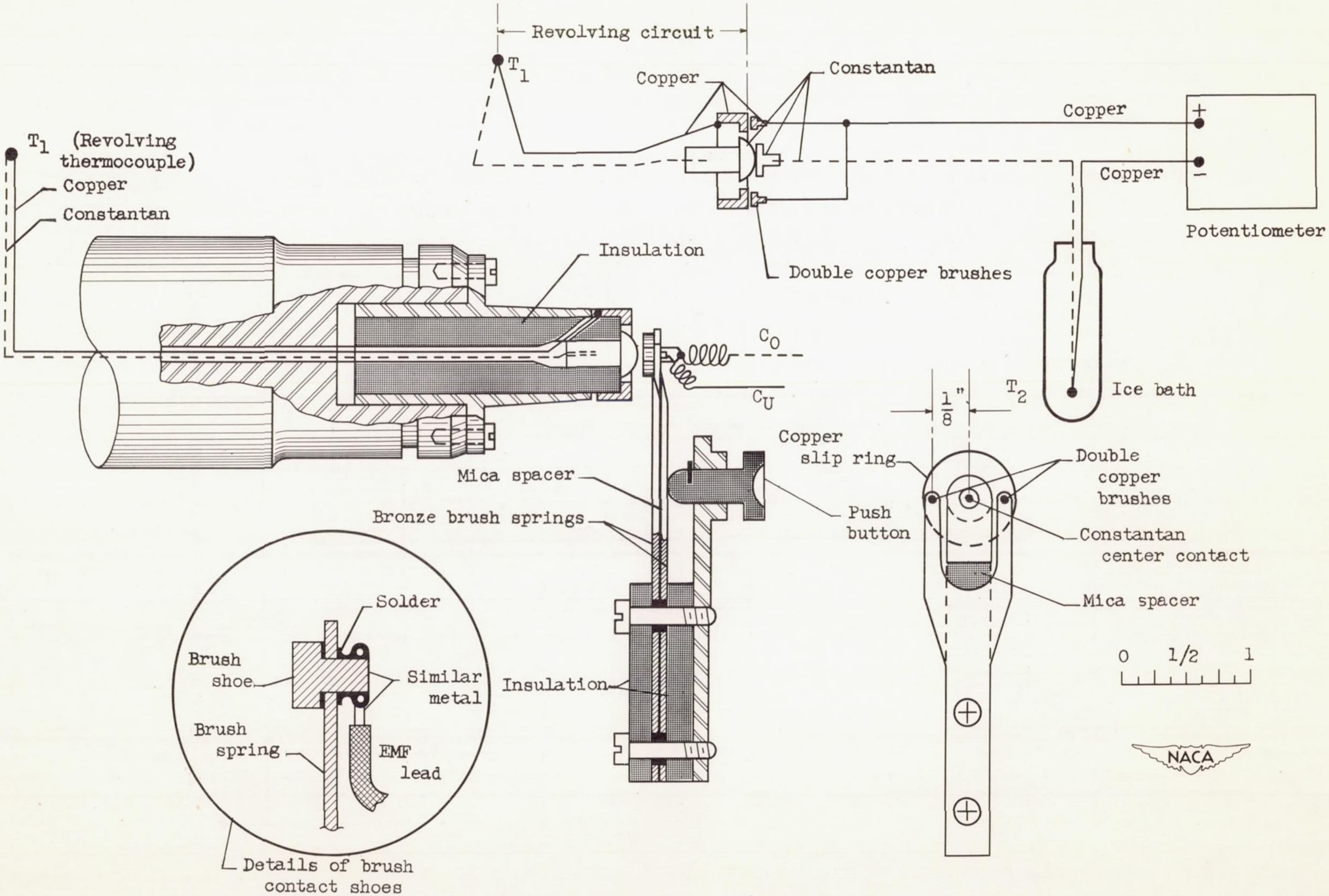


Figure 14. - Copper-constantan center-contact thermocouple pickup unit for use at speeds up to 50,000 rpm.